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**Modeling an analytics system for industrial safety monitoring based on expert assessments**

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*Introduction.* A mathematical model of the industrial safety monitoring system in mechanical engineering is investigated. The work objective was to create a mathematical model based on expert assessments of workplace safety parameters with a calculated and experimental justification of its applicability to the "STRAZH" expert security monitoring system.
*Materials and Methods*. The classification of expert systems for engineering enterprises is proposed. The stages of creating expert systems are considered. A methodology for assessing the consistency of experts as a basis for models of expert systems in the field of mechanical facilities safety is presented.
*Results*. The basic safety parameters of the workplace are identified. A matrix of expert evaluation of parameters based on the opinion of leading experts in the field of engineering is created. The results of modeling the expert system "STRAZH" with the calculated and empirical support of the mathematical model validity are presented. The advantages of implementing expert systems to increase the level of personnel safety are proved.
*Discussion and Conclusions.* The results obtained have a high degree of expert coordination and can be used in the development of expert safety monitoring systems for engineering enterprises.

**Keywords**: modeling, expert systems, knowledge base, expert assessment, mechanical engineering, safety parameters, concordance.

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**Introduction.** Difficult-to-formalize processes complicate full automation of engineering production. Smart manufacturing, smart enterprise and similar structures are implemented only on the basis of analysis information systems (AIS) using the components of artificial intelligence. At present, a uniform, classical definition of smart manufacturing is not presented in the technical and specialized literature. However, experts agree that "smart manufacturing", "smart enterprise", "smart factory" refers primarily to a widespread use of information technologies, computing devices, sensors and distributed networks to implement a highly efficient production process and provide its participants with maximum safety [1].

A modern approach to the development of intelligent AIS for smart manufacturing involves a widespread use of new methods for representing knowledge and programmed empirical algorithms for their processing [2].

First of all, among the AIS used in mechanical engineering, we single out two most promising classes.

1. Management information systems (MIS) are designed for monitoring and management of difficult-to-formalize process facilities. Core components in the MIS structure include:

— module for collection and processing databulk (big data) according to certain algorithms;

— module for the expert assessment formation [3].

2. Expert systems (ES) are designed for the collection, processing and analysis of formalized experience of experts in a specific field of engineering. Core components in the structure of ES include:

— module for the accumulation of expert knowledge in a specific field of engineering;

— module for the formation of alternative control scenarios under specific conditions based on the empirical experience of experts [4].

AIS of both classes are complex software systems created to replicate empirical experience and algorithms developed on its basis to increase the efficiency of engineering industries.

The knowledge base is the central system component that is formed in the process of ES modeling, designing and operating. The main difference between ES and other information systems involves the solution to a clearly limited range of problems in a specific area [5]. Unlike traditional machine solutions, ES use not a procedural analysis, but the processing of deductive reasoning. Similar systems can find a solution to poorly defined and unstructured problems [6].

**Materials and Methods**

**ES in Mechanical Engineering.** In the modern world, the accumulated, processed and analyzed knowledge is used for monitoring, preventing and forecasting emergencies that is the result of empirical studies of several generations of experts. In this regard, ES are essential in the modeling and prediction of dangerous events.

MIS and ES are designed in two stages:

— designing a module for the accumulation and structuring of knowledge in a specific field;

— designing a module for developing recommendations and making a control decision based on specific facts and parameters for monitoring the state of an object.

The use of ES in the field of labor protection at engineering enterprises is due to the need to reproduce the knowledge of experienced experts. This is one of the conceptual stages in the development of digital production. From the user point of view, ES are of interest at this time for a number of reasons:

— they can solve various practical problems and in terms of results are not inferior to expert people;

— they are focused on solving a wide range of tasks in nonformalized areas;

— they do not require special programming skills, and working with them is available for a wide audience of qualified users [7].

In mechanical engineering, ES help to make decisions, manage facilities, identify emergencies and failures, and design production. Fig. 1 shows the basic classes of problems solved by ES in mechanical engineering [8].

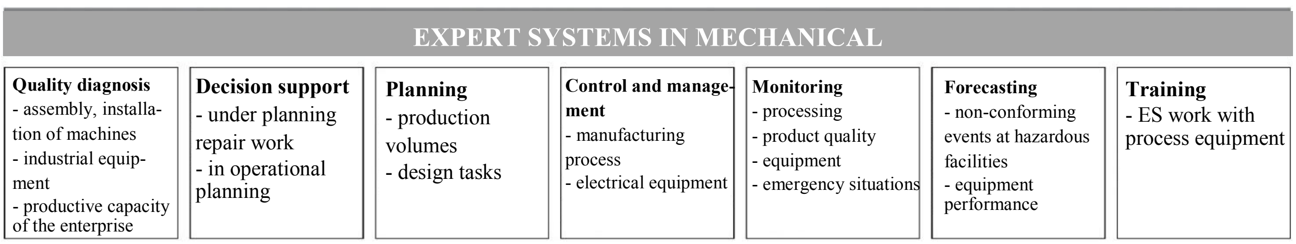


Fig. 1. Basic classes of problems solved by expert systems in engineering

In the practice of machine-building industries for TV-7 machines equipped with a function for controlling the accuracy of product processing, ES of the "Archimedes 2008" type are used. Under processing, the base circles in the cross and longitudinal sections and geometric parameters are calculated using the "Archimedes 2008" system to identify possible deviations. At the same time, problems with deviation of the longitudinal section profile, deviation from roundness, ovality, are identified, errors of sizing, waviness, etc., are determined [9].

The experience of using ES in mechanical engineering made it possible to identify the main advantages of their implementation:

- an increase in the quality of decisions made,
- improving the quality of manufactured products,
- increase in productivity,
- advanced training of employees.

It should be noted that it is advisable to use ES to solve complex problems in engineering production [10].

The key concept of labor protection in mechanical engineering is “workplace”. This is the place where an employee should be located or where he needs to arrive in connection with his job. It is directly or indirectly controlled by the employer. Workplace safety is regulated by the Occupational Safety Standards System SSBT (GOST 12). It should be noted that ES do not provide for full control of safety at the workplace.

To increase the reliability of control decisions, a generalized expert assessment should be introduced into the workplace safety model. The key point in conducting an expert assessment is the selection of competent specialists with experience in the claimed field and capable of an adequate assessment of the technological situation [11].

**Research objective** is to develop a mathematical model and conduct a calculation and experimental justification of its applicability for ES security monitoring “STRAZH” (“System for the exact calculation of vital activity algorithms), based on the analysis of the subject area and expert assessments.

**Initial data.** Based on the analysis of literary sources and the opinion of practitioners, 11 basic parameters of workplace safety were identified.

1. Equipment (functional content).
2. Compliance of the equipment with the anthropometric characteristics of an employee.
3. The availability of personal and collective protective equipment, as well as fire extinguishing equipment.
4. Access to the workplace and the ability to quickly evacuate.
5. Serviceability of production equipment.
6. Performing production operations in accordance with the requirements of technological documentation.
7. Monitoring of distributed hazardous and harmful factors.
8. Keeping the established order and organization, high production, technological and labor discipline.
9. Qualification of the employee.
10. Timely training and retraining of the employee.
11. Regular monitoring.

The totality of data on the key parameters of the workplace safety provides you for such a characteristic of the work process as labor intensity. This integrated characteristic of the labor process shows the load on the nervous system, sensory organs, and considers the emotional component. Labor intensity is normalized by types of loads: intellectual, sensory, emotional, monotonous, and operational.

**Development of mathematical model of the ES “STRAZH”.** When developing the mathematical model of the ES “STRAZH”, 21 experts evaluated the safety parameters of the workplace on a scale from 1 to 12 points. The survey was conducted using questionnaires. Based on its results, a consolidated matrix for assessing workplace safety parameters has been created (Fig. 2).

| PARAMETERS | EXPERTS | | | | | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 | 16 | 17 | 18 | 19 | 20 | 21 |
| Production equipment serviceability | 11 | 10 | 11 | 11 | 12 | 11 | 12 | 10 | 11 | 8 | 11 | 10 | 10 | 11 | 12 | 11 | 10 | 11 | 10 | 11 | 7 |
| Access to workplace and ability to quickly evacuate | 10 | 11 | 12 | 10 | 9 | 10 | 7 | 9 | 7 | 5 | 10 | 11 | 12 | 10 | 10 | 7 | 12 | 10 | 11 | 8 | 10 |
| Availability of personal protective equipment and fire extinguishing | 9 | 9 | 9 | 8 | 10 | 9 | 9 | 11 | 9 | 9 | 12 | 9 | 8 | 9 | 9 | 10 | 9 | 9 | 9 | 9 | 11 |
| Compliance of equipment to human anthropometry | 5 | 6 | 5 | 7 | 5 | 5 | 6 | 5 | 5 | 2 | 5 | 5 | 6 | 4 | 6 | 5 | 6 | 5 | 7 | 5 | 3 |
| Monitoring of distributed hazardous and harmful factors | 12 | 12 | 10 | 12 | 11 | 12 | 11 | 12 | 12 | 12 | 9 | 12 | 11 | 12 | 11 | 12 | 11 | 12 | 12 | 12 | 9 |
| Employee qualifications | 2 | 2 | 2 | 2 | 4 | 2 | 2 | 3 | 2 | 10 | 2 | 2 | 2 | 2 | 3 | 2 | 2 | 2 | 2 | 2 | 6 |
| Workplace equipment | 6 | 5 | 6 | 6 | 6 | 6 | 5 | 6 | 6 | 6 | 6 | 6 | 5 | 6 | 5 | 6 | 3 | 6 | 6 | 6 | 5 |
| Performance of production operations due to requirements | 4 | 4 | 4 | 4 | 2 | 3 | 4 | 4 | 4 | 4 | 4 | 4 | 4 | 5 | 4 | 4 | 5 | 4 | 4 | 4 | 8 |
| Employee training and retraining | 7 | 7 | 8 | 5 | 7 | 8 | 10 | 7 | 10 | 7 | 7 | 7 | 7 | 7 | 7 | 9 | 8 | 7 | 5 | 7 | 4 |
| Keeping order and discipline | 3 | 3 | 3 | 3 | 3 | 4 | 3 | 2 | 3 | 3 | 3 | 3 | 3 | 3 | 2 | 3 | 4 | 3 | 3 | 3 | 12 |
| Monitoring regularity | 8 | 8 | 7 | 9 | 8 | 7 | 8 | 8 | 8 | 11 | 8 | 8 | 9 | 8 | 8 | 8 | 7 | 8 | 8 | 10 | 2 |

Fig. 2. Workplace safety rating matrix

A key outcome of the peer review methodology is Kendall's concordance coefficient, which measures the consistency of the expert group:

$$W = \frac{12 \cdot S}{m^2 \cdot (n^3 - n)}\ , \tag{1}$$

where $W$ is the concordance coefficient, $m$ is the number of experts, $n$ is the number of parameters, $S$ is the sum of squared deviations of the rank sums obtained by each parameter from the average rank sum of ranks.

The sum of squared rank deviations $S$ is calculated from the formula:

$$S = \sum_{i=1}^{n} D_i^2 = \sum_{i=1}^{n} (d_i - \overline{d})_i^2\ , \tag{2}$$

where $D_i$ is the rank deviation, $i$ is the serial number of the parameter, $d_i$ is the parameter rank, $\overline{d}$ is the arithmetic mean of the parameter rank.

The concordance coefficient varies in the range from 0 to 1: 0 corresponds to the complete inconsistency of experts, 1 corresponds to complete coordination. If the concordance coefficient is equal to zero, it is necessary to check the initial data and (or) analyze the membership of experts in order to replace them (partly or completely). If the coefficient value exceeds 0.4–0.5, the quality of the assessment is considered satisfactory, if it reaches 0.7–0.8 — high.

Thus, when calculating the concordance coefficient according to the formulas (1) and (2), we obtain the following parameter values:

$$S = \sum_{i=1}^{n} (d_i - \overline{d})^2 = 5476 + 2916 + \ldots + 361 = 39142\,,$$

$$W = \frac{12 \cdot S}{m^2 \cdot (n^3 - n)} = \frac{12 \cdot 39142}{21^2 \cdot (11^3 - 11)} = 0.806\,.$$

Using Pearson's "chi-square" criterion [12], the null hypothesis $h_0$: $W = 0$ (expert opinions do not agree with each other), at an alternative $h_1$: $W \neq 0$ (expert opinions are consistent with each other) is tested.

We introduce expert estimates, rank sums $d_i$, rank sum deviations $D_i$ from the average $\overline{d}$ and $D_i^2$ in the design Table 1.

Table 1

The concordance coefficient calculation

| | Experts | | | | | | | | | | | | | | | | | | | | | $d_i = \sum_{j=1}^{m} R_{ij}$ | $D_i$ | $D_i^2$ |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Parameters | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 | 16 | 17 | 18 | 19 | 20 | 21 | | | |
| 1 | 11 | 10 | 11 | 11 | 12 | 11 | 12 | 10 | 11 | 8 | 11 | 10 | 10 | 11 | 12 | 11 | 10 | 11 | 10 | 11 | 7 | 221 | 74 | 5476 |
| 2 | 10 | 11 | 12 | 10 | 9 | 10 | 7 | 9 | 7 | 5 | 10 | 11 | 12 | 10 | 10 | 7 | 12 | 10 | 11 | 8 | 10 | 201 | 54 | 2916 |
| 3 | 9 | 9 | 9 | 8 | 10 | 9 | 9 | 11 | 9 | 9 | 12 | 9 | 8 | 9 | 9 | 10 | 9 | 9 | 9 | 9 | 11 | 196 | 49 | 2401 |
| 4 | 5 | 6 | 5 | 7 | 5 | 5 | 6 | 5 | 5 | 2 | 5 | 5 | 6 | 4 | 6 | 5 | 6 | 5 | 7 | 5 | 3 | 108 | –39 | 1521 |
| 5 | 12 | 12 | 10 | 12 | 11 | 12 | 11 | 12 | 12 | 12 | 9 | 12 | 11 | 12 | 11 | 12 | 11 | 12 | 12 | 12 | 9 | 239 | 92 | 8464 |
| 6 | 2 | 2 | 2 | 2 | 4 | 2 | 2 | 3 | 2 | 10 | 2 | 2 | 2 | 2 | 3 | 2 | 2 | 2 | 2 | 2 | 6 | 58 | –89 | 7921 |
| 7 | 6 | 5 | 6 | 6 | 6 | 6 | 5 | 6 | 6 | 6 | 6 | 6 | 5 | 6 | 5 | 6 | 3 | 6 | 6 | 6 | 5 | 118 | –29 | 841 |
| 8 | 4 | 4 | 4 | 4 | 2 | 3 | 4 | 4 | 4 | 4 | 4 | 4 | 4 | 5 | 4 | 4 | 5 | 4 | 4 | 4 | 8 | 87 | –60 | 3600 |
| 9 | 7 | 7 | 8 | 5 | 7 | 8 | 10 | 7 | 10 | 7 | 7 | 7 | 7 | 7 | 7 | 9 | 8 | 7 | 5 | 7 | 4 | 151 | 4 | 16 |
| 10 | 3 | 3 | 3 | 3 | 3 | 4 | 3 | 2 | 3 | 3 | 3 | 3 | 3 | 3 | 2 | 3 | 4 | 3 | 3 | 3 | 12 | 72 | –75 | 5625 |
| 11 | 8 | 8 | 7 | 9 | 8 | 7 | 8 | 8 | 8 | 11 | 8 | 8 | 9 | 8 | 8 | 8 | 7 | 8 | 8 | 10 | 2 | 166 | 19 | 361 |
| | | | | | | | | | | | | | | | | | | | | | | **1617** | | **39142** |

The average rank sum of all parameters is $\overline{d} = \dfrac{\sum_{j=1}^{m} R_{ij}}{n} = \dfrac{1617}{11} = 147.$

We use the expression $\overline{d} = \dfrac{1}{2} \cdot m \cdot (n+1) = \dfrac{1}{2} \cdot 21 \cdot (11+1) = 147.$ as a control of calculations.

To test the null hypothesis using Pearson's "chi-square" criterion, we calculate the empirical value $\chi^2 = m \cdot (n-1) \cdot W = 21 \cdot 10 \cdot 0.806 = 169.4$, which is compared to the critical values of "chi-square" for the number of degrees of freedom $n-1=10$.

The empirical value $\chi^2 = 169.4$ falls into the critical region $\chi^2 > \chi^2_{0,01}(n-1)$ ($169.4 > 23.2$), which allows us to reject the null hypothesis. The concordance coefficient differs significantly from zero; therefore, there is a fairly close consistency of expert opinions regarding the estimated parameters.

**Research Results.** An ES is developed in three stages: modeling, design, construction [13]. At the modeling stage, an analysis of the subject area to identify the most significant links and relationships between objects is carried out; the totality of input and output parameters, the degree of their input on the processes under study are determined. To build a mathematical model of the ES "STRAZH", the safety parameters of workplaces of the machine-building industries were identified. When assessing safety parameters, it became necessary to select empiric experts who were the most competent in the organization of the mechanical engineering processes, since there are no methods to guarantee single-value safety assessments. The experts selected were occupational safety engineers from leading enterprises of mechanical engineering in the Rostov Region, as well as leading lecturers from the Engineering Technology Department, Don State Technical University.

**Discussion and Conclusions.** According to the study, the concordance coefficient reached 0.806. This indicates a high consistency of expert opinions. It is verified by Pearson's criterion and is a prerequisite for the development of a high-precision ES model.

In modern science, a significant place is occupied by the problem of decision support using ES. The introduction of such systems in mechanical engineering will enable:

— to reduce the time on solving complex security issues;

— to reduce the likelihood of producing spurious solution;

— to raise the level of labor safety.

The study of this issue in the context of modern innovative production is of current interest.

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